Safety Effectiveness of Intersection Left- and Right-Turn Lanes

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SAFETY EFFECTIVENESS OF INTERSECTION LEFT- AND RIGHT-TURN LANES

by

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ABSTRACT. This paper presents the results of research that performed a well-designed before-after evaluation of the safety effects of providing left- and right-turn lanes for at-grade intersections. Geometric design, traffic control, traffic volume, and traffic accident data were gathered for a total of 280 improved intersections, as well as 300 similar intersections that were not improved during the study period. The types of improvement projects evaluated included installation of added left-turn lanes, added right-turn lanes, and extension of the length of existing left- or right-turn lanes. An observational before-after evaluation of these projects was performed using several alternative evaluation approaches. Three contrasting approaches to before-after evaluation were used: the yoked comparison or matched-pair approach, the comparison group approach, and the Empirical Bayes approach. The research not only evaluated the safety effectiveness of left- and right-turn lane improvements, but also compared the performance of these three alternative approaches in making such evaluations. The research developed quantitative safety effectiveness measures for installation design improvements involving added left-turn lanes and added right-turn lanes. The research concluded that the Empirical Bayes method provided the most accurate and reliable results. Further use of this method is recommended.

INTRODUCTION

This paper presents the results of research on the safety effectiveness of installing left- and right-turn lanes for at-grade intersections. A key feature of the study is the comparison of three alternative approaches to the conduct of observational before-after safety evaluations. A full report on the research is available from the Federal Highway Administration (*1*).

LITERATURE REVIEW AND RESEARCH PRIORITIES

The research began with a review of published literature related to the safety effectiveness of intersection design and traffic control elements. This review summarized current knowledge on the safety effects of a broad range of intersection features. Safety effectiveness estimates were found for many of those features but, in many cases, those estimates are of questionable validity because they were based on studies that were poorly designed and executed. Based on the literature review, it was decided that the research should focus on quantifying the safety effectiveness of left- and right-turn lanes through a well-designed before-after evaluation.

A key feature of the before-after evaluation was that it was conducted not only to assess the safety effectiveness of intersection left- and right-turn lanes, but also to compare three statistical methods for performing such evaluations and assess the relative effectiveness of those methods. The three evaluation approaches that were considered are discussed later in the paper.

SELECTION OF EVALUATION SITES

Three types of sites were identified and selected for the study: *improved* or *treatment* sites, *comparison* sites, and *reference* sites. The database assembled for the study included 580 intersections of these three types, as explained below.

The improved or treatment sites are intersections at which a left- or right-turn lane was added and for which data on intersection geometrics, traffic volumes, and traffic accidents are available for time periods before and after the improvement. These improvements were made at existing unsignalized intersections, existing signalized intersections, and newly signalized intersections where a turn lane was added at the same time that a signal was installed at a previously unsignalized intersection. A total of 280 intersection improvement projects of the following types were evaluated:

- Added left-turn lanes
- Added right-turn lanes
- Added left- and right-turn lanes at the same intersection
- Extension of the length of an existing left- or right-turn lane

Tables 1 and 2 summarize the number and type of improved sites for rural and urban intersections respectively. The intersection types shown in the table include:

- Existing unsignalized intersections (all of these intersections had stop sign control on the minor road and no control on the major road)
- Existing signalized intersections
- Newly signalized intersections (i.e., existing unsignalized intersections at which signal control and one or more turn lanes were added as part of the same improvement project)

Only projects at three- and four-leg intersections were considered. Approximately one-third of the improved intersections have three legs and two-thirds have four legs. The evaluation sites include nearly equal numbers of rural and urban intersections. All of the evaluation sites had either two-way STOP control or traffic signal control. Approximately 57 percent of the evaluation sites were at existing two-way stop-controlled intersections, 26 percent were at existing signalized intersections, and 17 percent were at newly signalized intersections. Approximately 80 percent of the evaluation sites had painted left-turn channelization, while 20 percent of sites had curbed left-turn channelization. Approximately 82 percent of the signalized intersections with left-turn lanes also had protective/permissive signal phasing; 13 percent of signalized intersections had protected phasing, while 5 percent had no left-turn phasing. All of the improvement projects evaluated were constructed during the years 1989 through 1998; the vast majority of the sites were improved during the period from 1994 through 1997.

The intersections were located in eight of the states that participated in the study: Illinois, Iowa, Louisiana, Minnesota, Nebraska, North Carolina, Oregon, and Virginia. The states supplied descriptions of the improvement projects, as well as traffic volume and accident data for the study sites, and permitted the research team to visit the sites and document intersection features.

The improvement projects evaluated at existing unsignalized intersections included only projects in which turn lanes were added on the major road approaches; projects with turn lanes added on the minor-road stop-controlled approaches were not considered.

For 260 of the 280 improved intersections (93 percent), a matching comparison site that was not improved during the study period was selected. The matching improved and comparison sites were always in the same state and were located geographically close to one another whenever practical. The matching sites were as similar to one another as possible in intersection configuration, traffic control, geometric design, and traffic volume. It was not feasible to match the paired treatment and comparison sites based on accident frequency because the comparison sites were identified before the accident data on those sites was obtained. However, a comparison between the accident frequencies of the treatment and comparison groups as a whole showed similar patterns of variation over time *(1)*. The other 20 improved sites were sufficiently unique that no matching comparison site could be found. The research evaluated intersections that were selected for improvement prior to the beginning of the study. Thus, the research team had no influence over which locations were chosen for improvement and which were not. For this reason, a randomized experimental design was not feasible and an observation approach was, therefore, used.

In addition, 40 reference sites were selected. The reference sites were unimproved intersections that were not matched to any particular improved site. These reference sites were used to expand the available sample size of unimproved sites.

DATA COLLECTION

An extensive data collection effort was carried out for the improved, comparison, and reference sites. Geometric design and traffic control data were obtained from field visits to nearly every study intersection.

Traffic volume data for both the major- and minor-road legs were obtained from counts or estimates for as many years as possible for each intersection from highway agency records. Intersections were included in the study only if average daily traffic (ADT) volumes for the major and minor roads were available for at least one year during the study period. Traffic volume estimates for each individual year of the study period were obtained through a careful process of interpolation and extrapolation. Only limited data were available on hourly turning movement volumes at the study intersections. However, it is reasonable to assume that changes in turning movement volumes from before to after the improvement were in rough proportion to the changes in the major- and minor-road ADTs.

Traffic accident records from each participating highway agency for periods before and after each of the improvement projects were evaluated. The evaluation generally included all accidents within 75 m (250 ft) of each intersection that were designated by the investigating officer or accident coder as being related to the presence of the intersection. The database assembled for the 580 study intersections included a total of 26,056 intersection-related accidents (123 fatal accidents, 10,203 nonfatal injury accidents, and 15,730 property-damage-only accidents).

STUDY PERIODS

The accident database used in the study included 9 to 13 years of data for each intersection. Study periods before and after each improvement project were defined with durations as long as possible, consistent with the availability of data. The data for the year in which the project was constructed was not included in either the before or after study period. The before study periods for the treatment sites ranged from 1 to 10 years, with a mean duration of 6.7 years. The after study periods also ranged from 1 to 10 years, but with a lower mean duration of 3.9 years.

MEASURES OF EFFECTIVENESS

Evaluations of the safety effectiveness of turn-lane improvements are presented in this paper for three safety measures of effectiveness:

- All accidents (i.e., accidents of all types and severity levels)
- Fatal-and-injury accidents
- Project-related accidents (i.e., accidents involving vehicle movements associated with the specific turn lanes that were installed)

Evaluations were also conducted for project-related fatal-and-injury accidents, but restriction of the safety measure of effectiveness to only selected collision types and only selected severity levels reduced the available sample sizes so much that no useful results were obtained.

Separate evaluations were conducted for total intersection accidents (i.e., accidents that occurred within or were related to each intersection as a whole) and intersection approach accidents (i.e., only those accidents related to the specific intersection approaches on which turn lanes were installed).

EVALUATION APPROACHES

Overview of Alternative Evaluation Approaches

Three alternative statistical approaches were used to evaluate the effectiveness of the intersection improvement projects. These alternative approaches were:

- Before-after evaluation with yoked comparisons
- Before-after evaluation with a comparison group
- Before-after evaluation with the Empirical Bayes approach

These approaches were developed from those recommended by Griffin and Flowers (*2*) and by Hauer (*3*). The yoked-comparison (YC) approach is a traditional approach to the evaluation of traffic accident countermeasures and involves one-to-one matching between improved and comparison sites. The safety performance of the matched comparison site is used to estimate what change in safety would have occurred at the improved site had the improvement not been made. The comparison-group (CG) approach is similar to the YC approach, but replaces the single comparison site matched to each improved site with a group of similar sites whose collective safety performance serves the same function. The Empirical Bayes (EB) approach replaces the comparison group with the use of a negative binomial regression model used to predict the change in safety performance at the improved site that would have been expected had the improvement not been made. Figure 1 illustrates the conceptual approaches employed by the three methods.

When an intersection has relatively high accident experience during a particular time period, its annual accident frequency is likely to decrease even if it is not improved; this phenomenon is known as *regression to the mean*. Thus, when an improvement project is constructed at an intersection with relatively high accident experience, the natural decrease in accident frequency due to regression to the mean may be mistaken for an effect of the project. Thus, regression to the mean is a major threat to the validity of before-after evaluations.

The EB approach is the only known technique to account for the effect of regression to the mean on evaluation results. The YC and CG approach can account for the effects of changes in traffic volume levels and for general time trends in accident frequency, but not for regression to the mean. The CG approach is generally preferable to the YC approach because the CG approach uses multiple comparison sites for each improved site and because, as implemented in this evaluation, it has a more sophisticated method to account for traffic volume changes than the YC approach.

Description of Alternative Evaluation Approaches

The three alternative analysis approaches share similar approaches to formulation of the effectiveness measure for a before-after evaluation. These approaches can best be described in terms of four observed accident frequencies:

K_i = observed number of accidents at treatment site *i* during the before period
L_i = observed number of accidents at treatment site *i* during the after period
M_i = observed number of accidents at comparison site *i* during the before period
N_i = observed number of accidents at comparison site *i* during the after period

Yoked Comparison Approach

In the YC approach, for any pair of treatment and comparison sites (designated by subscript *i*), the expected number of accidents at the treated site in the after period had no improvement been made ($\hat{\pi}_i$), is best estimated as:

$$\hat{\pi}_i = K_i\left(\frac{N_i}{M_i}\right) \tag{1}$$

The best estimate of the expected number of accidents after the treatment ($\hat{\lambda}_i$) is the observed accident frequency. In other words:

$$\hat{\lambda}_i = L_i \tag{2}$$

The expected number of accidents without the treatment, ($\hat{\pi}_i$) is then compared to the observed number of accidents, $\hat{\lambda}_i$ or L_i, to assess the accident reduction effectiveness of the project at that site. The accident reduction effectiveness of the project can be assessed as the ratio of what the accident experience was with the treatment to what it would have been without the treatment:

$$\hat{\theta}_i = \hat{\lambda}_i / \hat{\pi}_i = L_i / \hat{\pi}_i \tag{3}$$

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or, equivalently:

$$\hat{\theta}_i = \hat{\lambda}_i \,/\, \hat{\pi}_i = \frac{L_i \; M_i}{K_i \; N_i} \tag{4}$$

The parameter $\hat{\theta}_i$ is known as the odds ratio for the treatment. When $\hat{\theta}_i < 1$, the accident frequency has decreased and the treatment appears to be effective; when $\hat{\theta}_i > 1$, the accident frequency has increased and the treatment appears to be harmful to safety. The treatment effectiveness can also be expressed as the percentage change in the expected accident frequency, E, estimated as 100 ($\hat{\theta}$ – 1). A negative value of E represents a reduction in accident frequency. If the before and after periods differ in duration, or if traffic volumes have changed between the before and after periods, corrections for these changes need to be incorporated in Equations (1) and (3). In the YC approach, these corrections are simple proportions. A more sophisticated correction for traffic volumes, used in the other approaches, is discussed below.

Equations (1) through (4) deal with the estimated treatment effectiveness at a single site. An overall estimate of the treatment effectiveness for a particular type of improvement can be derived from the effectiveness estimates for the individual sites using a weighted average. The weight, w_i, for each site represents the reciprocal of the squared standard error of the log odds ratio, R_i, generated from the data for that site, or:

$$R_i = \ln\left(\frac{L_i \; M_i}{K_i \; N_i}\right) = \ln \hat{\theta}_i \tag{5}$$

The squared standard error for R_i is calculated as:

$$R^2_{i(se)} = \frac{1}{K_i} + \frac{1}{L_i} + \frac{1}{M_i} + \frac{1}{N_i} \tag{6}$$

from which the weight, w_i, is simply calculated as:

$$w_i = 1 \,/\, R^2_{i(se)} \tag{7}$$

A weighted average (mean) log odds ratio across all n pairs of sites can be determined as:

$$R_{mean} = \frac{\Sigma w_i \; R_i}{\Sigma w_i} \tag{8}$$

By exponentiating Equation (8), an overall average (mean) odds ratio, or project effectiveness measure, can be obtained for the *n* sites as:

$$\theta_{mean} = e^{R_{mean}} \tag{9}$$

Thus, the overall mean percentage accident reduction effectiveness of a treatment can be estimated as:

$$E_{mean} = 100\ (\theta_{mean} - 1) \tag{10}$$

The next step in the analysis is to assess whether the estimated effectiveness, θ_{mean}, is statistically significantly different from one, or whether the mean percentage accident reduction effectiveness is statistically significantly different from zero. Since R_{mean} is asymptotically normally distributed, a z-test is used to test for significance, as follows. The standard error of R_{mean} is computed as:

$$R_{mean(se)} = 1/\sqrt{\sum w_i} \qquad (11)$$

A standard normal z-score can then be obtained as:

$$z = R_{mean} / R_{mean(se)} \qquad (12)$$

If z falls within the interval from –1.96 to +1.96, then one should conclude that there is no apparent treatment effect at the 95-percent confidence level. If z falls outside the interval from –1.96 to +1.96, then one should conclude that there is a statistically significant treatment effect (beneficial if z is negative, harmful if z is positive).

Using Equations (9) through (11), the standard error of E_{mean} is computed as:

$$E_{mean} = 100\,\theta_{mean} / \sqrt{\sum w_i} \qquad (13)$$

Comparison Group Approach

The key features that distinguish the CG approach from the YC approach are:

- The estimate of the odds ratio, $\hat{\theta}_i$, for each treated site is based on a group of comparison sites rather than a single yoked comparison site.
- The effect on safety of changes in traffic volumes between the before and after period is accounted for by a more sophisticated methodology. Rather than using a correction based on the ratio of the after period to before period traffic volumes, the correction is based on ratios between the accident frequencies predicted by a safety performance function (SPF) for the different traffic volume levels. In this case, the SPF is a negative binomial regression model of the relationship between intersection accident frequency and the average daily traffic volumes entering the intersection.

A new procedure, consistent with the approach formulated by Hauer (3), was developed to apply the correction for the durations and the traffic volumes of the before and after study periods in the CG approach. This new procedure, which is documented by Harwood et al. *(1)*, was needed for this research because the year in which each treatment was implemented differed between treatment sites so that, even though the same comparison group was used for all treatment sites, the various treatments required the use of different years of data from the comparison group sites for the before and after periods.

The statistical significance of the effectiveness measure, θ_{mean} or E_{mean}, is determined by the same procedure as shown in Equations (11) through (13).

It should be noted that, while the formulation of the CG approach is based, in part, on concepts presented by Hauer (*3*), Hauer himself does not consider the CG approach satisfactory because it does not address the issue of regression to the mean.

Empirical Bayes Approach

The key difference between the EB approach and the other approaches discussed above is that the EB approach does not use any explicit comparison site or comparison group to estimate the ratio, M_i/N_i. Instead, $\hat{\pi}_i$, the expected number of accidents at the treatment site in the after period, had the treatment not been made, is estimated from:

- The observed number of accidents at the treatment site during the before period, Ki.
- The expected number of accidents at the treatment site during the before period, estimated from an SPF (i.e., a negative binomial regression model) like that used for the traffic volume correction in the CG approach.

These observed and expected accident frequencies are combined using a weighting procedure presented by Hauer (*3*) and the result is then adjusted for differences in duration and traffic volumes between the before and after periods.

The statistical significance of the effectiveness measures, θ_{mean} and E_{mean}, is assessed by determining whether the ratio of $E_{mean}/E_{mean(se)}$ is greater than 2.0. This procedure, recommended by Hauer (*3*), is analogous to the procedure for the YC and CG approaches using Equations (11) through (13).

Comparison of Alternative Evaluation Approaches

The discussion of the three evaluation methods presented above makes clear that, on conceptual and theoretical grounds, the EB approach appears to be the most desirable of the three approaches. The primary reason for this is that, among the three approaches, only EB can account for regression to the mean. When comparing the CG and YC methods, the CG method is most desirable on conceptual and theoretical grounds because it uses a group of comparison sites, rather than a single site, to determine what would have happened at the treatment site had the improvement not been made. The use of multiple comparison sites should reduce the variance of the treatment effect and provide more accurate results. Thus, the three evaluation approaches, in descending order of theoretical appropriateness and potential accuracy, are EB, CG, and YC.

The evaluation results obtained in the study appear to confirm our initial expectations concerning the suitability of the three evaluation approaches. Table 3 presents a summary of the frequency with which various types of results were obtained with each approach. The table includes for each project type the number of evaluations with statistically significant results obtained with the YC, CG, and EB methods; the number of evaluations with statistically significant results for the EB and at least one of the other approaches; and the relative magnitudes of the EB effectiveness estimates and the effectiveness estimates obtained from the other approaches. The latter item (relative magnitudes) includes three categories (EB below YC and CG, EB between YC and CG, and EB above YC and CG).

Table 3 is interpreted as follows. First, the table shows that, for the 110 analyses performed, there were 46 statistically significant results for the EB approach, 45 for the CG approach, and 34 for the YC approach. While not definitive, this result is consistent with the theoretical expectation that the EB and CG approaches are preferable to the YC approach.

Second, for 32 cases where statistically significant results were obtained with the EB approach and at least one of the other approaches, the project effectiveness determined with the EB approach was lower than with the YC and CG in 18 cases and was higher in only six cases. The generally lower project effectiveness estimates obtained with the EB approach are consistent with it being less affected by regression to the mean than the YC and CG approaches.

Both of these observations from Table 3 appear to confirm that the EB approach is the most suitable approach, followed by the CG approach, and then the YC approach. These findings support the use of the EB results, in preference to the CG and YC results, whenever the EB results are statistically significant.

The following criteria were used in this research to determine which set of evaluation results to use:

- Use the effectiveness measure determined from the EB approach, if it is statistically significant.
- If the effectiveness measure determined from the EB approach is not statistically significant, but the effectiveness measure from the CG approach is statistically significant, use the CG result.
- If the effectiveness measures from both the EB and CG approaches are not statistically significant, but the effectiveness measure from the YC approach is statistically significant, use the YC result.

The YC and CG results identified by these guidelines were reviewed individually and were each found to be more credible than the non-statistically-significant EB results.

EVALUATION RESULTS

The evaluation results indicating the effectiveness of turn lanes in improving safety are presented in the following discussion.

Table 4 presents the final evaluation results for adding left-turn lanes at specific types of four-leg intersections. Table 5 presents comparable data for adding left-turn lanes at three-leg intersections. The percentage changes in accident frequency shown in these tables are generally negative because they represent reductions in accidents. For unsignalized and newly signalized intersections, only left-turn lanes added on the major-road approaches to the intersection were evaluated. The tables shows the expected percentage change in accident frequency for each project type. The negative values for percentage change in accident frequency indicates that these changes represent reductions in accident frequency. The value following the plus or minus sign is the standard error of the percentage change in accident frequency, which is a measure of the precision of the expected value. The smaller the standard error, the more precise the estimate of the expected value. The effectiveness estimates are based on the EB approach whenever that approach provided statistically significant results. When the results from the EB approach were not statistically significant, the results of the CG approach or, if necessary, the YC approach were used.

Table 6 presents comparable evaluation results for adding right-turn lane on the major-road approaches to four-leg intersections. Only limited results were obtained for adding right-turn lanes on major-road approaches to three-leg intersections.

Summary tables have been developed combining the results obtained in this study with results previous reported in the literature. Tables 7 and 8 summarize the safety effectiveness of installing left-turn lanes on the major-road approaches to rural and urban intersection, respectively. Table 9 presents comparable effectiveness estimates for right-turn lanes that are applicable to both rural and urban intersections. The safety effectiveness of adding turn lanes is presented in the tables as the expected percentage reduction in total intersection accidents. All of the results in Tables 7 through 9 were derived in the current study except where noted; the full research report includes estimates of the precision of each of these results (*1*). Effectiveness measures for situations not addressed in the current study were based on the findings of an expert panel convened to assess published literature in another recent FHWA study (*4*). Furthermore, all of the results from the current study shown in Tables 7 through 9 are based on the EB approach, with one exception noted in Table 8.

The effectiveness of projects involving the addition of both left- and right-turn lanes on the major road at the same intersection can be determined by combining the relevant effectiveness measures from Tables 1 through 3. For example, at an urban four-leg signalized intersection, the addition of two major-road left-turn lanes would be expected to reduce total intersection accidents by 19 percent and the addition of two major-road right-turn lanes would be expected to reduce accidents by 8 percent. The combined effectiveness would be computed as 1-(1-0.19) (1-0.08) = 0.25, or a 25-percent reduction in total intersection accidents. This approach assumes that the safety effects of adding left- and right-turn lanes are independent. Some highway agencies have found the assumption of independence to be overly optimistic. In the above example, it is likely that the combined effect is in the range between the larger of the two separate effects and the computed combined effect (i.e., in the range from 19 to 25 percent).

No reliable effectiveness measures were found for extending the length of an existing left- or right-turn lanes.

FINDINGS

The findings of the research are as follows:

1. Added left-turn lanes are effective in improving safety at signalized and unsignalized intersections in both rural and urban areas. Installation of a single left-turn lane on a major-road approach would be expected to reduce total intersection accidents at rural unsignalized intersections by 28 percent for four-leg intersections and by 44 percent for three-leg intersections. At urban unsignalized intersections, installation of a left-turn lane on one approach would be expected to reduce accidents by 27 percent for four-leg intersections and by 33 percent for three-leg intersections. At four-leg urban signalized intersections, installation of a left-turn lane on one approach would be expected to reduce accidents by 10 percent. The complete set of effectiveness measures for left-turn lane installation is presented in Tables 4 and 5.
2. Added right-turn lanes are effective in improving safety at signalized and unsignalized intersections in both rural and urban areas. Installation of a single right-turn lane on a major-road approach would be expected to reduce total intersection accidents at rural unsignalized intersections by 14 percent and accidents at urban signalized intersections by 4 percent. Right-turn lane installation reduced accidents on individual approaches to four-leg intersections by 27 percent at rural unsignalized intersections and by 18 percent at urban signalized intersections. The complete set of effectiveness measures for right-turn lane installation at four-leg intersections is presented in Table 6.
3. For both left- and right-turn lane improvements, the results obtained from this research are within the range of all previous studies reported in the literature, but are slightly higher than the best estimates from previous studies recently made by an expert panel (*1, 4*).
4. In the various evaluations performed, the effectiveness of turn-lane improvements in reducing fatal and injury accidents was greater than for total accidents, in some cases, and less than for total accidents in others. Overall, there is no indication that any type of turn-lane improvement is either more or less effective for different accident severity levels.
5. Tables 4 through 6 include estimates of the standard error of the mean improvement effectiveness. The standard error is a measure of the precision of the mean improvement

effectiveness (i.e., smaller standard errors represent more precise estimates). The most precise effectiveness estimates were generally obtained for the project and intersection types with the largest sample sizes, particularly added left-turn lanes at rural four-leg unsignalized intersections and at urban four-leg signalized intersections.

6. The EB approach to observational before-after evaluations of safety improvements appears to perform effectively. Comparisons of the EB approach to the YC and CG approaches found that the EB approach was more likely to provide statistically significant effectiveness measures. Furthermore, the effectiveness measures obtained from the EB approach were generally smaller than those from the other approaches; this may have resulted from reduced effect of the regression-to-the-mean phenomenon; compensation for regression to the mean is highly desirable in providing accurate evaluation results.

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REFERENCES

1. Harwood, D. W., K. M. Bauer, I. B. Potts, D. J. Torbic, K. R. Richard, E. R. Kohlman Rabbani, E. Hauer, and L. Elefteriadou. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes*, Federal Highway Administration, Report No. FHWA-RD-02-089, July 2002.
2. Griffin, L. I., and R. J. Flowers. "A Discussion of Six Procedures for Evaluating Highway Safety Projects," Federal Highway Administration, December 1997.
3. Hauer, E. *Observational Before-After Studies in Road Safety*, Pergamon/Elsevier Science, Inc., Tarrytown, New York, 1997.
4. Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes, and A. Vogt. *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*, Federal Highway Administration, Report No. FHWA-RD-99-207, December 2000.

LIST OF TABLES

TABLE 1 Number of Improved Sites at Rural Intersections

Intersection traffic control	Project type	Number of improved sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	0	21	0	1	14	4	14	7	61
	Added RTLs	14	18	0	0	0	0	5	4	41
	Added both LTLs and RTLs	1	21	0	0	1	0	2	2	27
	Extended LTLs	0	0	0	0	0	0	0	2	2
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	0	0	0	0	0	0	0	0	0
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
	Extended LTLs	0	0	0	0	0	0	0	7	7
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	1	1
Newly signalized intersections	Added LTLs	0	0	0	0	0	2	0	0	2
	Added RTLs	0	0	0	0	0	1	0	0	1
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
Total		15	61	0	1	18	4	21	23	143

LTL = Left-turn lane.
RTL = Right-turn lane.

TABLE 2 Number of Improved Sites at Urban Intersections

Intersection traffic control	Project type	Number of improved sites by state								
		IA	IL	LA	MN	NC	NE	OR	VA	Total
Existing unsignalized intersections	Added LTLs	2	6	1	2	0	5	4	0	20
	Added RTLs	1	3	0	0	0	0	0	0	4
	Added both LTLs and RTLs	0	1	0	0	0	0	0	0	1
	Extended LTLs	0	0	0	0	0	0	0	4	4
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Existing signalized intersections	Added LTLs	9	17	5	3	2	3	4	0	43
	Added RTLs	1	17	2	0	0	0	0	1	21
	Added both LTLs and RTLs	3	7	1	1	0	0	0	0	12
	Extended LTLs	0	0	0	0	0	0	0	0	0
	Extended both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Newly signalized intersections	Added LTLs	1	14	3	4	3	1	6	0	32
	Added RTLs	0	0	0	0	0	0	0	0	0
	Added both LTLs and RTLs	0	0	0	0	0	0	0	0	0
Total		17	65	12	10	5	9	14	5	137

LTL = Left-turn lane.
RTL = Right-turn lane.

TABLE 3 Comparison of Evaluation Approaches

Project type	Total number of evaluations performed[a]	Number of evaluations with statistically significant results			Number of evaluations with statistically significant results for EB approach and at least one other approach	Relative magnitude of EB effectiveness estimates in comparison to YC and CG effectiveness estimates		
		YC	CG	EB		EB below YC and CG	EB between YC and CG	EB above YC and CG
Added LTLs	40	28	27	24	21	13	6	2
Added RTLs	30	1	5	10	3	3	0	0
Added LTLs and RTLs	26	5	11	9	6	2	2	2
Extended LTLs and RTLs	14	0	2	3	2	0	0	2
	110	34	45	46	32	18	8	6

[a] Includes the evaluation results reported in Tables 4 through 6 and several others performed in the research (see Reference 1).

TABLE 4 Final Evaluation Results Involving Added Left-Turn Lanes for Four-Leg Intersections

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	–28 ± 2.6	–35 ± 3.0	–37 ± 7.4	–55 ± 2.4	–61 ± 3.2	–
Newly Signalized[b]	–35 ± 7.6	–29 ± 6.3	–	–44 ± 7.3	–42 ± 7.6	–
URBAN INTERSECTIONS						
Unsignalized[b]	–27 ± 3.0	–29 ± 4.0	–25 ± 7.2	–20 ± 4.4	–55 ± 4.8	–51 ± 7.3
Signalized	–10 ± 0.8	–9 ± 1.3	–13 ± 3.2	–34 ± 0.8	–35 ± 1.3	–40 ± 1.8
Newly Signalized[b]	–24 ± 2.8	–28 ± 5.0	–	–28 ± 2.9	–43 ± 4.0	–

Note: Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
[a] Includes accidents of all severity levels.
[b] Based on a limited number of sites.

TABLE 5 Final Evaluation Results Involving Added Left-Turn Lanes for Three-Leg Intersections

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	–44 ± 5.5	–55 ± 8.3	–62 ± 14.5	–45 ± 6.5	–44 ± 10.9	–64 ± 10.5
Newly Signalized[b]	–	–	–	–68 ± 9.3	–	–
URBAN INTERSECTIONS						
Unsignalized[b]	–33 ± 12.1	–	–	–32 ± 13.1	–	–
Signalized	–	–	–	–49 ± 13.9	–48 ± 23.4	–
Newly Signalized[b]	–	–	–	–	–	–

Note: Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
[a] Includes accidents of all severity levels.
[b] Based on a limited number of sites.

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TABLE 6 Final Evaluation Results for Projects Involving Added Right-Turn Lanes for Four-Leg Intersections

	Percent change in accident frequency for adding one turn lane ± standard error					
	Total intersection accidents			Intersection approach accidents		
	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]	All accidents[a]	Fatal and injury accidents	Project-related accidents[a]
RURAL INTERSECTIONS						
Unsignalized	–14 ± 5.2	–23 ± 6.6	–	–27 ± 5.3	–24 ± 7.9	–
Newly Signalized[b]	–	–	–	–	–66 ± 7.6	–
URBAN INTERSECTIONS						
Unsignalized[b]	–40 ± 10.1	–	–	–	–	–
Signalized	–4 ± 2.0	–9 ± 3.0	–	–18 ± 2.0	–22 ± 3.1	–

Note: Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
[a] Includes accidents of all severity levels.
[b] Based on a limited number of sites.

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TABLE 7 Expected Percentage Reduction in Total Accidents From Installation of Left-Turn Lanes on the Major-Road Approaches to Rural Intersections

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign[a]	44[b]	–
	Traffic signal	15[c]	–
Four-leg intersection	STOP sign[a]	28[b]	48[b]
	Traffic signal	18[c]	33[c]

[a] STOP signs on minor-road approach(es).
[b] Based on EB evaluation presented in this paper and in Reference 1.
[c] Based on Reference 4.

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TABLE 8 Expected Percentage Reduction in Total Accidents for Installation of Left-Turn Lanes on the Major-Road Approaches to Urban Intersections

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign[a]	33[b]	–
	Traffic signal	7[d]	–
Four-leg intersection	STOP sign[a]	27[c]	47[b]
	Traffic signal	10[b]	19[b]

[a] STOP signs on minor-road approach(es).
[b] Based on EB evaluation presented in this paper and in Reference 1.
[c] Based on CG evaluation presented in this paper and in Reference 1.
[d] Based on Reference 4.

TABLE 9 Expected Percentage Accident Reduction in Total Accidents from Installation of Right-Turn Lanes on the Major-Road Approaches to Rural and Urban Intersections

Intersection traffic control	Number of major-road approaches on which right-turn lanes are installed	
	One approach	Both approaches
STOP sign[a]	14[b]	26[b]
Traffic signal	4[c]	8[c]

[a] STOP signs on minor-road approach(es).
[b] Based on EB evaluation for rural intersections presented in this paper and in Reference 1.
[c] Based on EB evaluation for urban intersections presented in this paper and in Reference 1.

LIST OF FIGURES

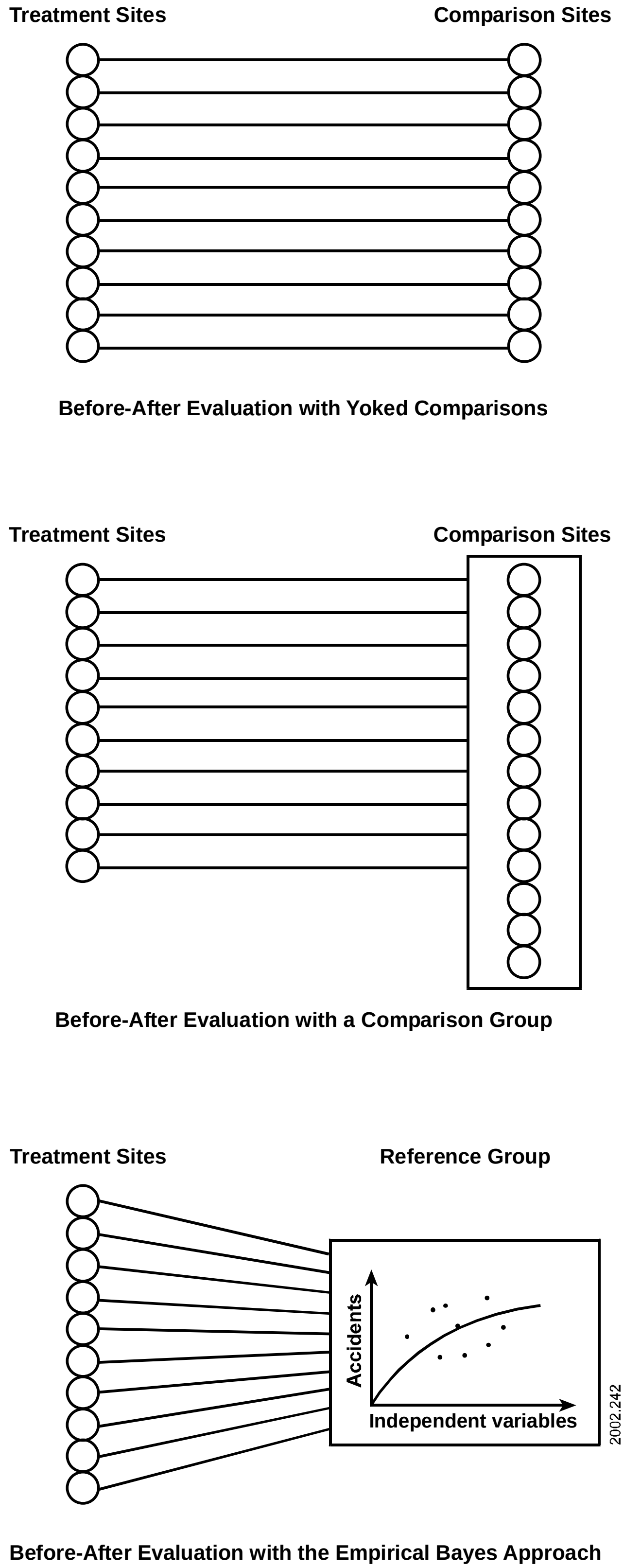

FIGURE 1 Conceptual comparison of evaluation approaches.

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